Dielectric Breakdown in Water with Nanosecond Laser Pulses

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1. Introduction

Recently, lasers have found numerous applications in medicine[1] in which the presence of water or liquid is essential for application. This increased the necessity of the studies on the interaction of laser radiation with liquids.[2]

In this paper, the probabilistic behavior of optical breakdown and the effect of diffusion on optical breakdown in distilled water are investigated using a Q-switched 0.532μ m laser with 5nsec duration.

2. Experimental Procedure

A Nd:YAG laser was Q-switched by a Pockels cell and its second harmonic 0.532 μ m with a pulse duration of 5nsec was used in the breakdown experiment. The laser beam was attenuated by neutral glass filters and focused into distilled water in a quartz cell by a lens with short focal length. The occurrence of breakdown was confirmed by the observation of a visible plasma emission and audible acoustic signature. The breakdown field was estimated from the measured laser power by joulemeter ED-100(Gentec Inc.) and the transmission rate of filters. Breakdown experiments were repeated 100times every 5 seconds at each laser field near breakdown.

(1) Optical field dependence of the breakdown probability

In this experiment a lens with 40mm focal length was used to cause breakdown in distilled water. The behavior of the breakdown probability was studied as a function of the laser intensity.[3] It was compared with the breakdown probability of air in which a avalanche mechanism is believed to govern the breakdown process. Further experiment is done in a solid PMMA in order to compare the probabilistic behavior of optical breakdown in gas, liquid and solid. In solid breakdown was confirmed by a microscope after 100 irradiations. After each irradiation the focal position of the laser was changed.

(2) Spot size dependence of optical breakdown

The influence of diffusion losses on the breakdown field was investigated by varying the focal length of the focusing lens.

When a laser beam with λ [m] wave length and d[m] diameter was focused with a lens of the f[m] focal length, the focused spot size r[m] of the laser is given by

$$r \propto \frac{\lambda}{d} f \qquad (1)$$

The smaller the focal length, the smaller the dimensions of the focal volume, the greater the rate of electrons out of it, and the higher the breakdown field.

In this experiment 6 lenses with different focal length (f=40mm, 50mm, 80mm, 100mm, 120mm, 150mm) were used in order to examine the spot size dependence of optical breakdown.

3. Experimental Results

Figure 1 shows plots of the breakdown probability versus the incident laser field in air, distilled water and solid PMMA. In this experiment, since the focal spot size of the laser beam was not measured, the root of the incident laser energy W into samples was used instead of laser field. The 50% probability breakdown field decreases and lies in a narrower field region with increasing the density of the sample (air→water→PMMA).

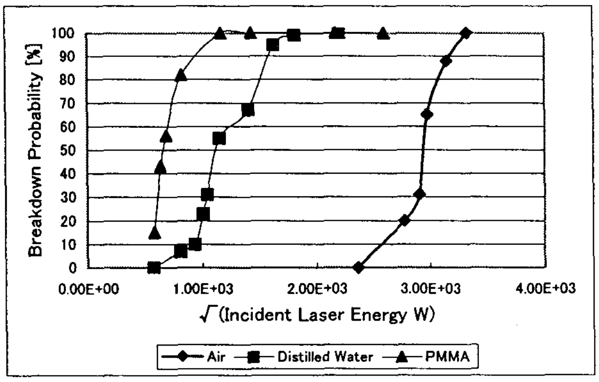
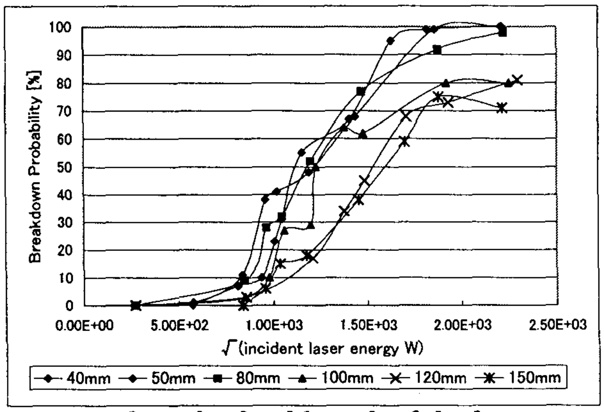


Fig.1. Breakdown probability vs. laser field in air, distilled water and solid PMMA.

Figure 2 shows plots of the breakdown probability versus the root of the incident laser energy when the lenses with focal length of 40, 50, 80, 100, 120 and 150mm were used. In this case the root of the incident laser energy is not in proportion to the laser field, since the focal spot size are not constant during the whole experiment. The root of the incident laser energy lies in a wider region with increasing the focal length of the lens.



when the focal length of the lens was varied.

4. Discussion

4.1 Confirmation of avalanche formation in water

Typical behavior of the breakdown probability, on logarithmic scale, versus the reciprocal laser field ($1/\sqrt{W}$) is shown in Fig.3, which is read from Fig.1.

The breakdown probability P depends on the laser field, E ($\sqrt{W}$), through the simple relation

$$P \propto \exp(-K/E) \qquad (2)$$

for values of P ranging from a few percents to more than 60~70% in distilled water. This dependence has been considered suggestive for an avalanche breakdown mechanism because the dc ionization coefficient that governs avalanche breakdown in gases and semiconductors depends on the electric field in the same manner.

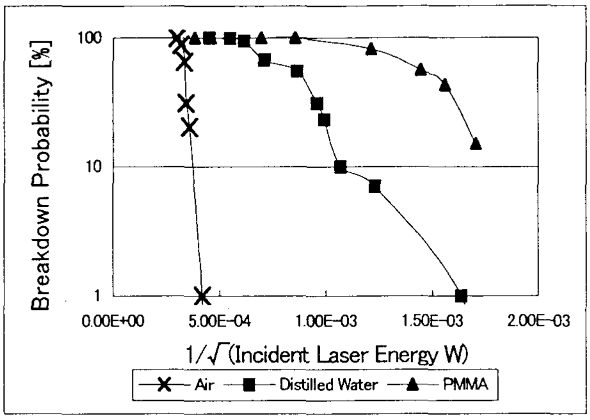


Fig.3. Breakdown probability on a logarithmic scale vs. reciprocal laser field.

In air the linearity of P vs. 1/E ($1/\sqrt{W}$) keeps in the whole region of the breakdown probability. In air, initial electrons are said to be produced by natural causes (cosmic radiation, etc.) and these electrons produce avalanche ionization. Therefore, the whole laser energy is used to produce avalanche ionization.

In distilled water, initial electrons are estimated to be supplied by multiphoton ionization of impurities in water. Since more laser energy is used to cause multiphoton ionization of impurities in the higher electric field region the probability data deviates from the linear curve in the region of the breakdown probability 60~100%.

In solid PMMA much data are not shown, but the data suggest us much more laser energy is used to supply initial electrons by multiphoton ionization.

4.2 Spot size dependence of optical breakdown

In this experiment the spot size of the focused laser beam has not been measured. So the focused radius r is assumed to be given by Eq.1 when the focal length was varied.

The laser field is in proportion to the root of the laser energy W divided by the square of the focal length f ($\sqrt{(w/f^2)}$). Figure 4 shows the 50% probability breakdown field of water as a function of the focal length, which is read from Fig.2. The breakdown field is constant when the focal length of the lens is from 150mm to 80mm.

The breakdown field increases with decreasing the focal length for the range less than 80mm. The smaller the focal length, the smaller the dimensions of the focal volume, the greater the rate of diffusion of electrons out of it, and the higher the breakdown field. For the range more than 80mm the diffusion time out of the focal volume is longer than the laser pulse duration. So the diffusion loss of electrons will be negligible and the breakdown field will be constant as shown in Fig.4.

A simple theory[4] will predict the breakdown field E is given by Eq.3

$$E \propto \sqrt{\frac{D}{r^2}} \qquad (3)$$

, where r is the radius of the focused laser beam and D is the diffusion constant. The radius r is proportion to the focal length f of the lens. So the breakdown field E is given by Eq.4

$$E \propto \frac{\sqrt{D}}{f} \qquad (4)$$

This dependence of the breakdown field on the focal length of the lens coincides with the experimental data for the range of the focal length f less than 80mm shown in Fig.4.

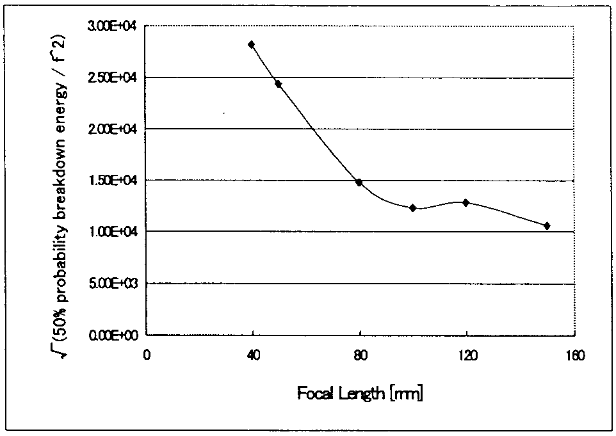


Fig.4. 50% probability field as a function of the focal length.

5. Conclusion

(1) The breakdown probability P of distilled water depends on the laser field E though the simple relation $P \propto \exp(-K/E)$. This suggests that the mechanism of laser-induced breakdown in distilled water is governed by the electron avalanche process.

(2) The role of diffusion losses on the laser-induced breakdown field was confirmed, when short focal length lenses are used.

References

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